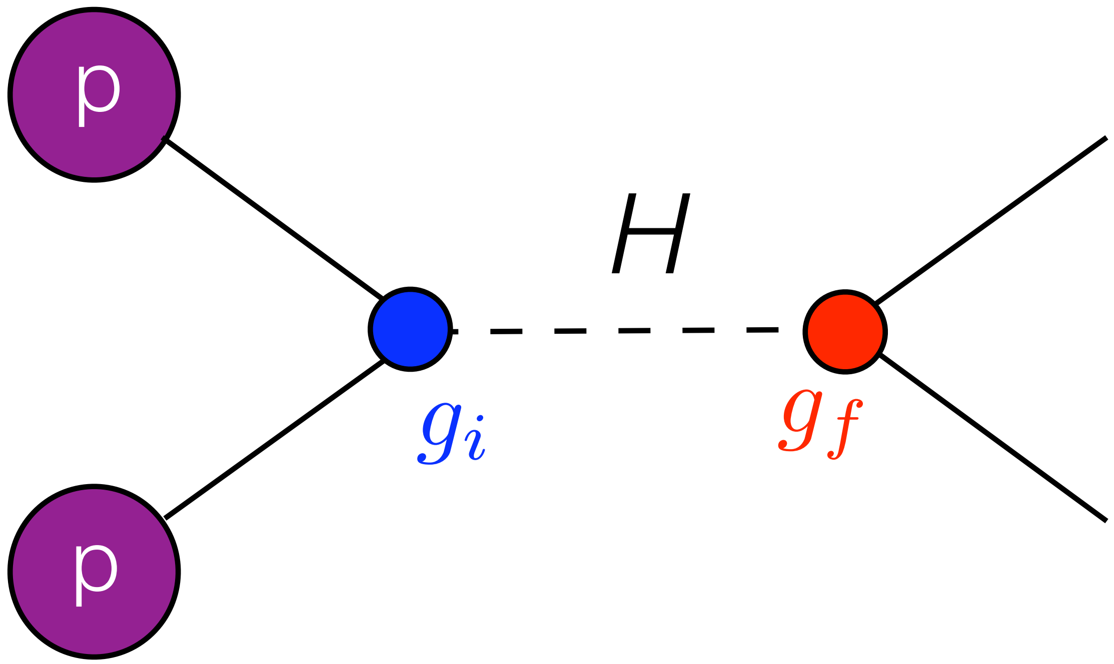
Bounding the Higgs width at the LHC

John Campbell, Fermilab

with K. Ellis, C. Williams;
1107.5569, 1311.3589, 1312.1628

Cross sections to parameters

- What is the theoretical expectation for the Higgs cross section?



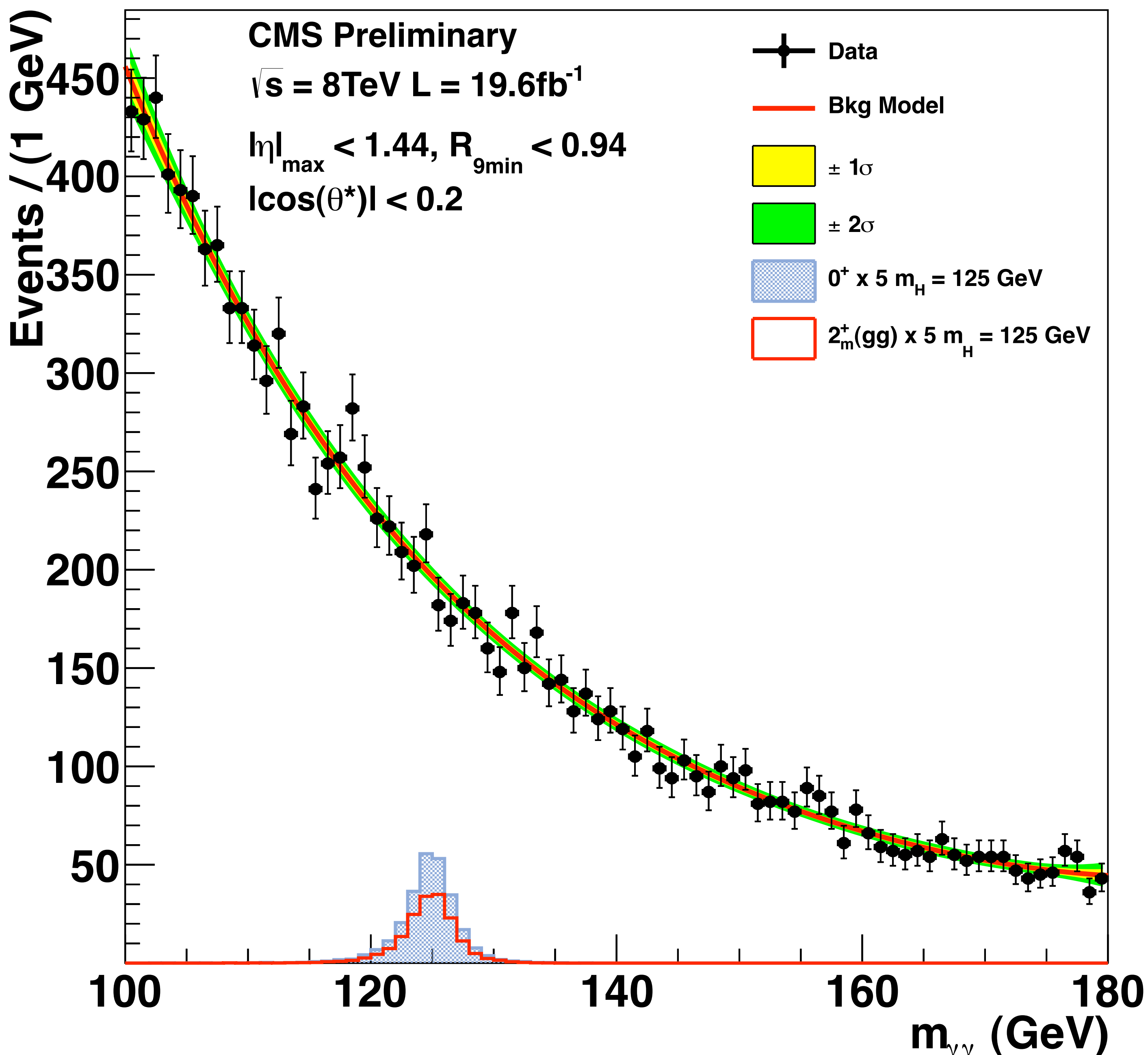
- Total cross section depends on the strengths of the couplings of the Higgs boson in production and decay stages g_i and g_f and also on the width of the resonance:

$$\sigma_{i \to H \to f} \sim \frac{g_i^2 \, g_f^2}{\Gamma_H}$$

- Focus of this talk: untangling the dependence to probe the width directly.

Constraints pre-Moriond 2014

- How can we probe a SM width of 4 MeV at the LHC?



CMS PAS HIG-13-016

- Intrinsic detector resolution is of order a few GeV in the most well-measured channels.
- Direct limits inherently weak:

$$\Gamma_H < 6.9 \text{ GeV}$$

$$(95\% \text{ confidence})$$

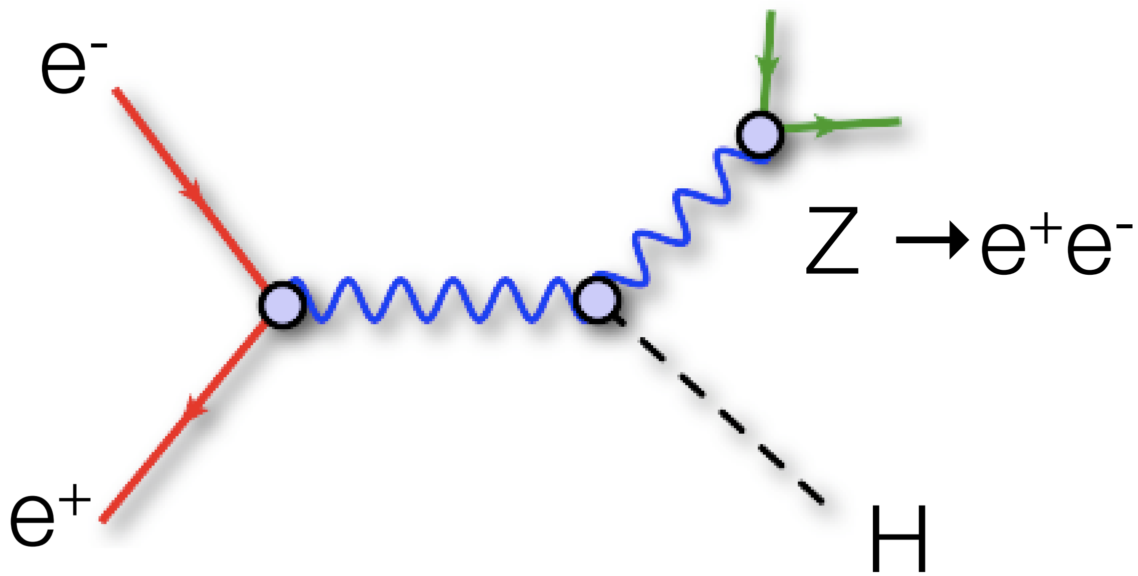
$$(\Gamma_H \lesssim 1600\,\Gamma_H^{\rm SM})$$

- Assume bound scales with statistics, combine with ZZ channel, 3000 fb^{-1}:

$$\Gamma_H \lesssim 200 \text{ MeV} \quad (\sim 50\,\Gamma_H^{\rm SM})$$

Future lepton colliders

- The width of the Higgs boson is a key deliverable of future lepton colliders.
- Clear strategy for an ILC.



- Tag ZH events where recoil mass is consistent with a Higgs boson → measurement of σ(ZH)
- Measurement of H→ZZ rate then determines Br(H→ZZ)

$$\begin{aligned} \Gamma_H &= \Gamma(H \to ZZ)/\mathrm{Br}(H \to ZZ) \\ &\propto \sigma(ZH)/\mathrm{Br}(H \to ZZ) \end{aligned}$$

- At 350 GeV and beyond (CLIC/TLEP), similar analysis through WW fusion.

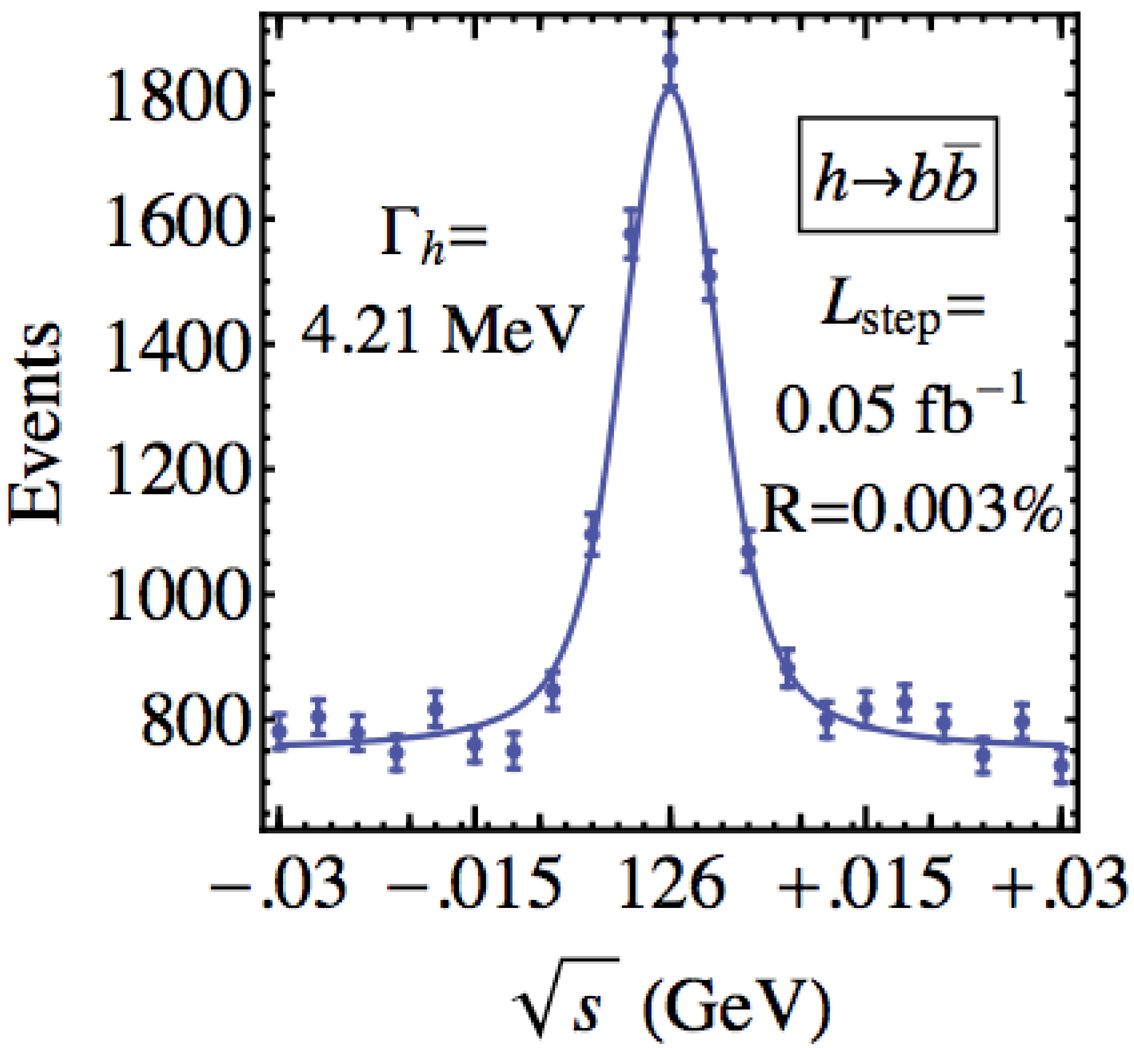
Facility		ILC		ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%

1%-10% precision

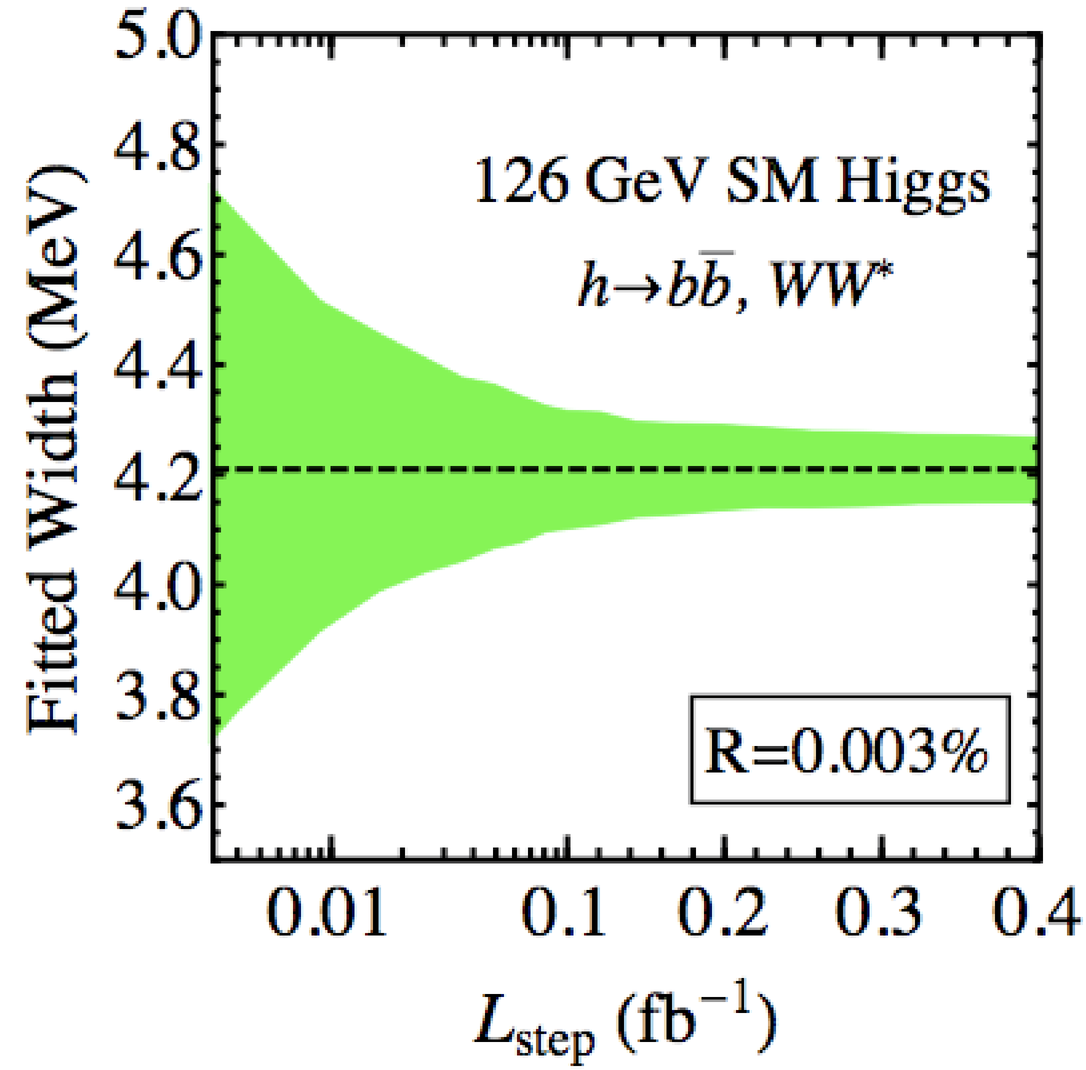
Snowmass Higgs WG,1310.8361

Future lepton colliders

- Muon collider: direct scan of Higgs threshold.
- Biggest systematic uncertainty from knowledge of muon beam.



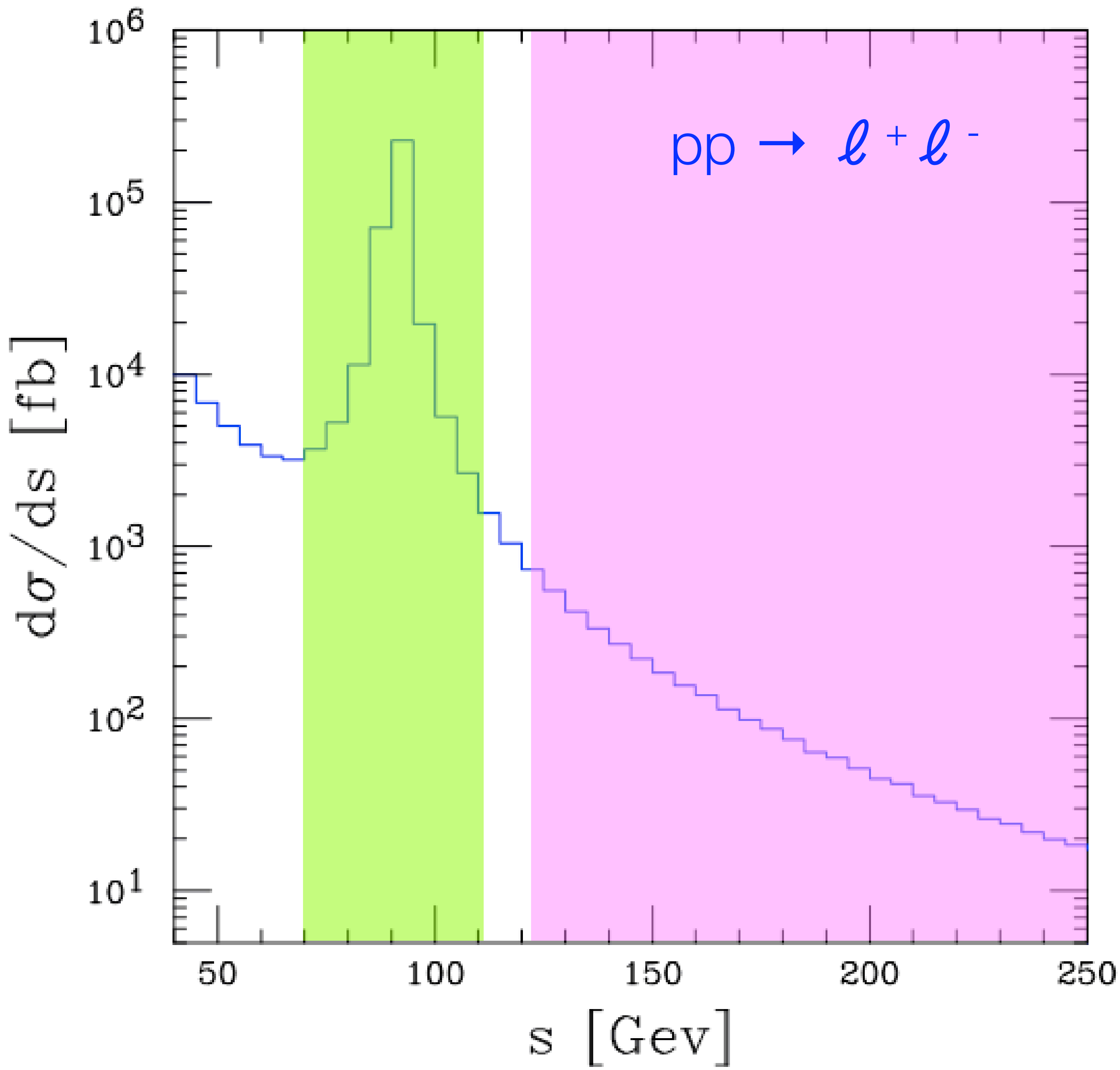
Muon collider Higgs factory study,1308.2143



~5% precision

Sketch of Caola-Melnikov method (essence of 1307.4935)

- Consider the Drell-Yan process. Can map out the resonance as a function of the four-momentum squared (*s*) that appears in the propagator.



- "On-shell" cross section in resonance region:

$$\sigma_{\rm on} \sim \int \frac{{\rm d}s}{(s-m_Z^2)^2+\Gamma_Z^2 m_Z^2} \propto \frac{1}{\Gamma_Z}$$

- "Off-shell" cross section above the resonance:

$$\sigma_{\rm off} \sim \int_{s \gg m_Z^2} \frac{{\rm d}s}{(s-m_Z^2)^2+\cancel{\Gamma_Z^2 m_Z^2}}$$

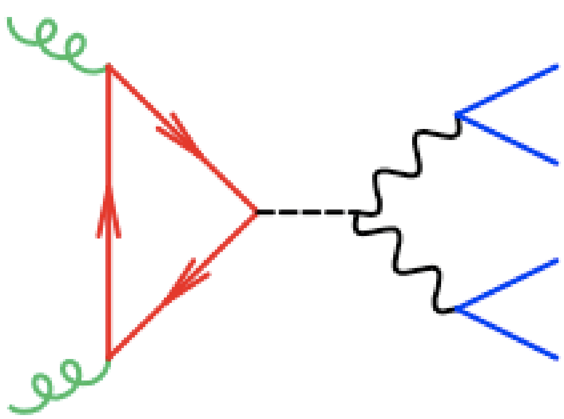
(approx.) independent of width.

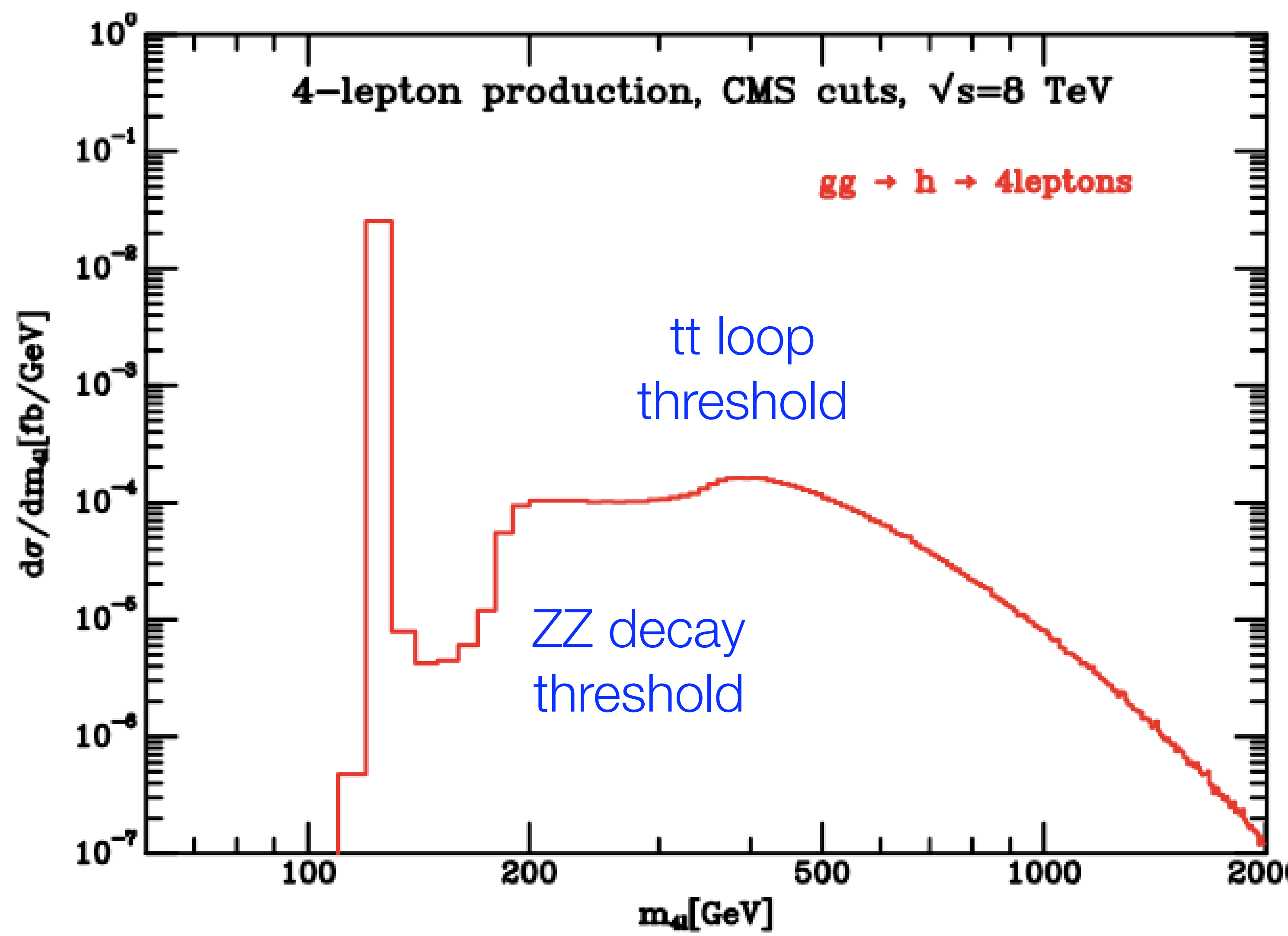
- Form ratio: $$\Gamma \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}}$$

How does it work for the Higgs boson?

- Naive expectation: $\Gamma_H / m_H \sim 10^{-5}$; resonance peak so narrow that there is no off-shell cross section to measure.
- This is spectacularly wrong for the golden channel.

$$p + p \to H \to ZZ$$
$$\quad\hookrightarrow \mu^- + \mu^+$$
$$\quad\hookrightarrow e^- + e^+ .$$





- About 15% of the total cross section in the region with $m_{4\ell} > 130$ GeV.

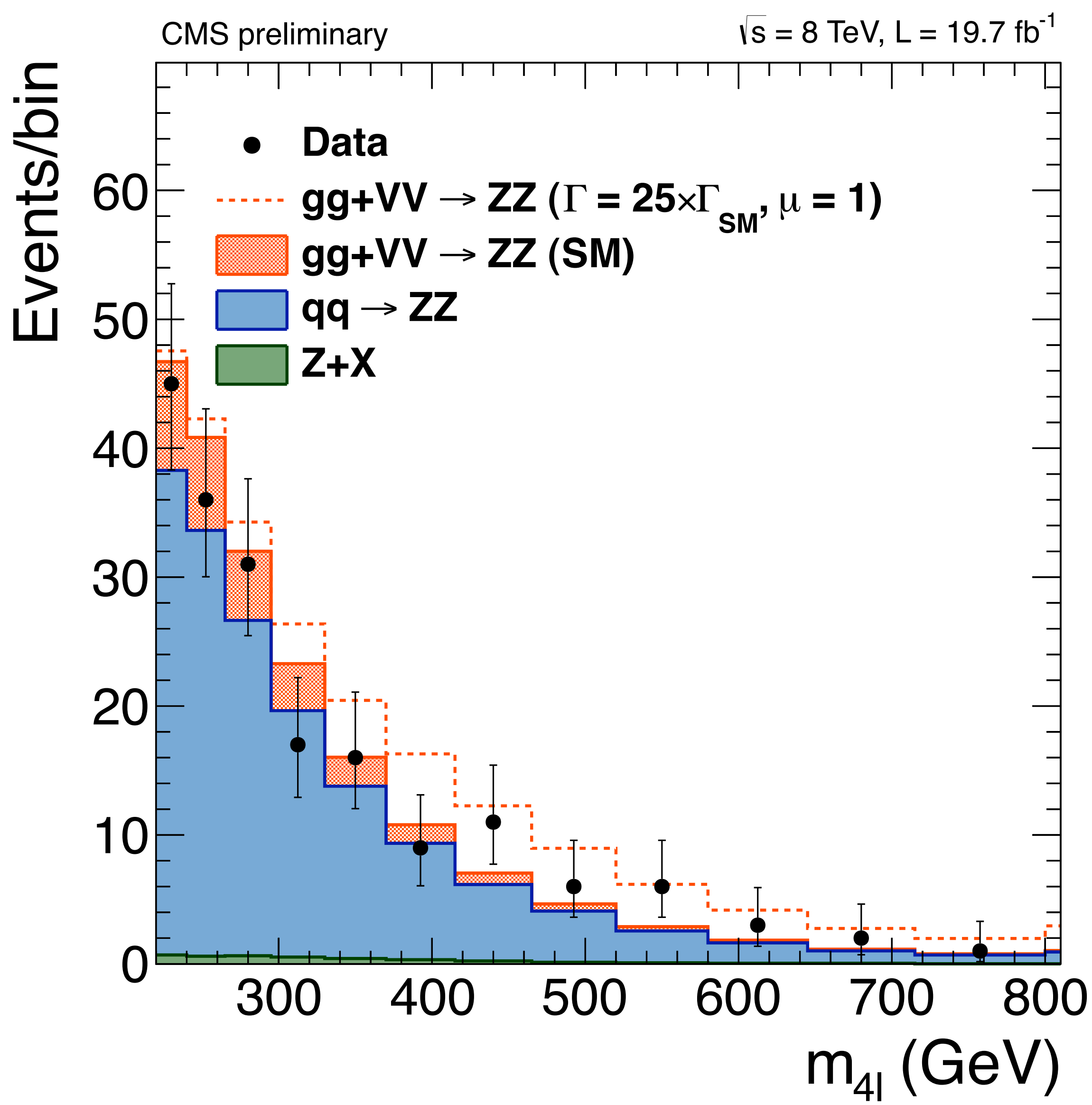
  Kauer, Passarino,1206.4803

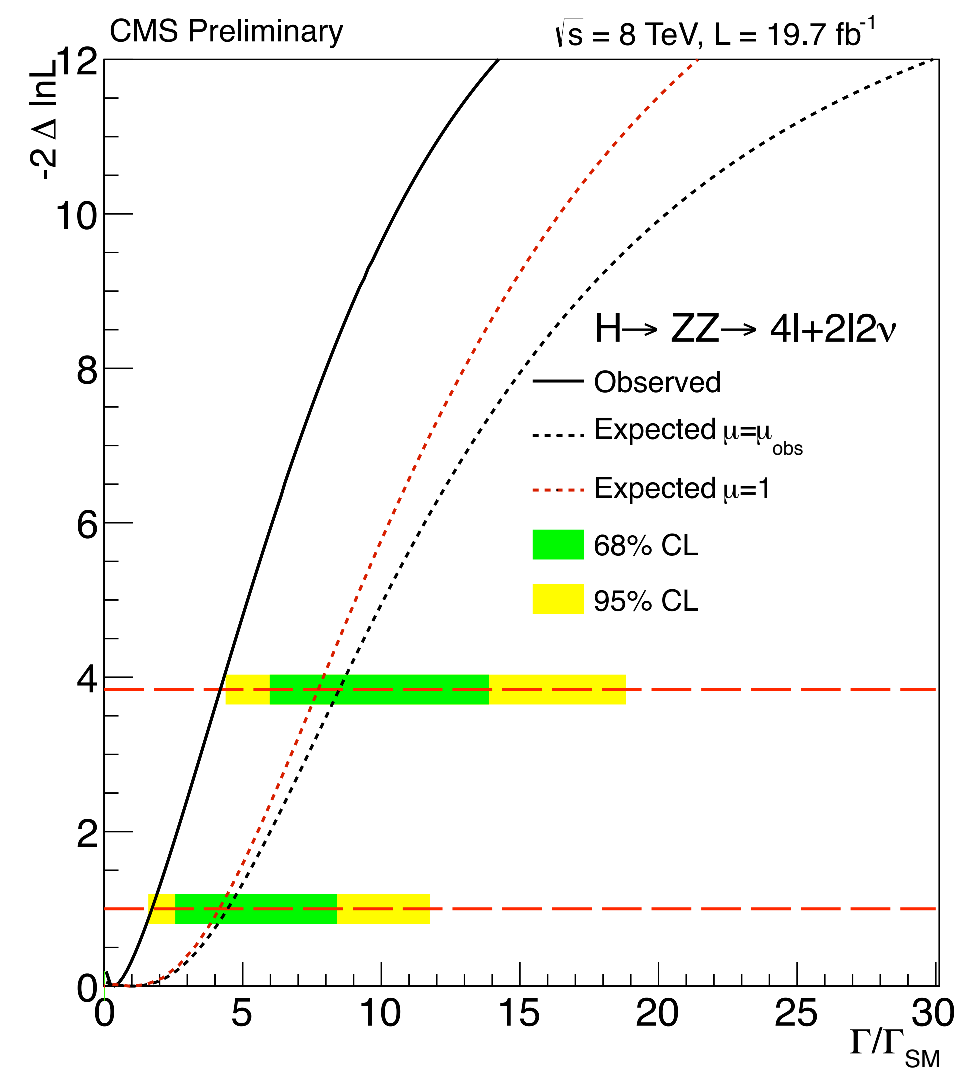
The CMS result PAS HIG-14-002

$$\Gamma \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}} \longrightarrow$$

if the peak cross section is in agreement with the SM expectation, a larger Higgs boson width means more off-shell events

$$\mathbf{\Gamma_H < 4.2 \times \Gamma_H^{SM}} \text{ at 95\% confidence}$$

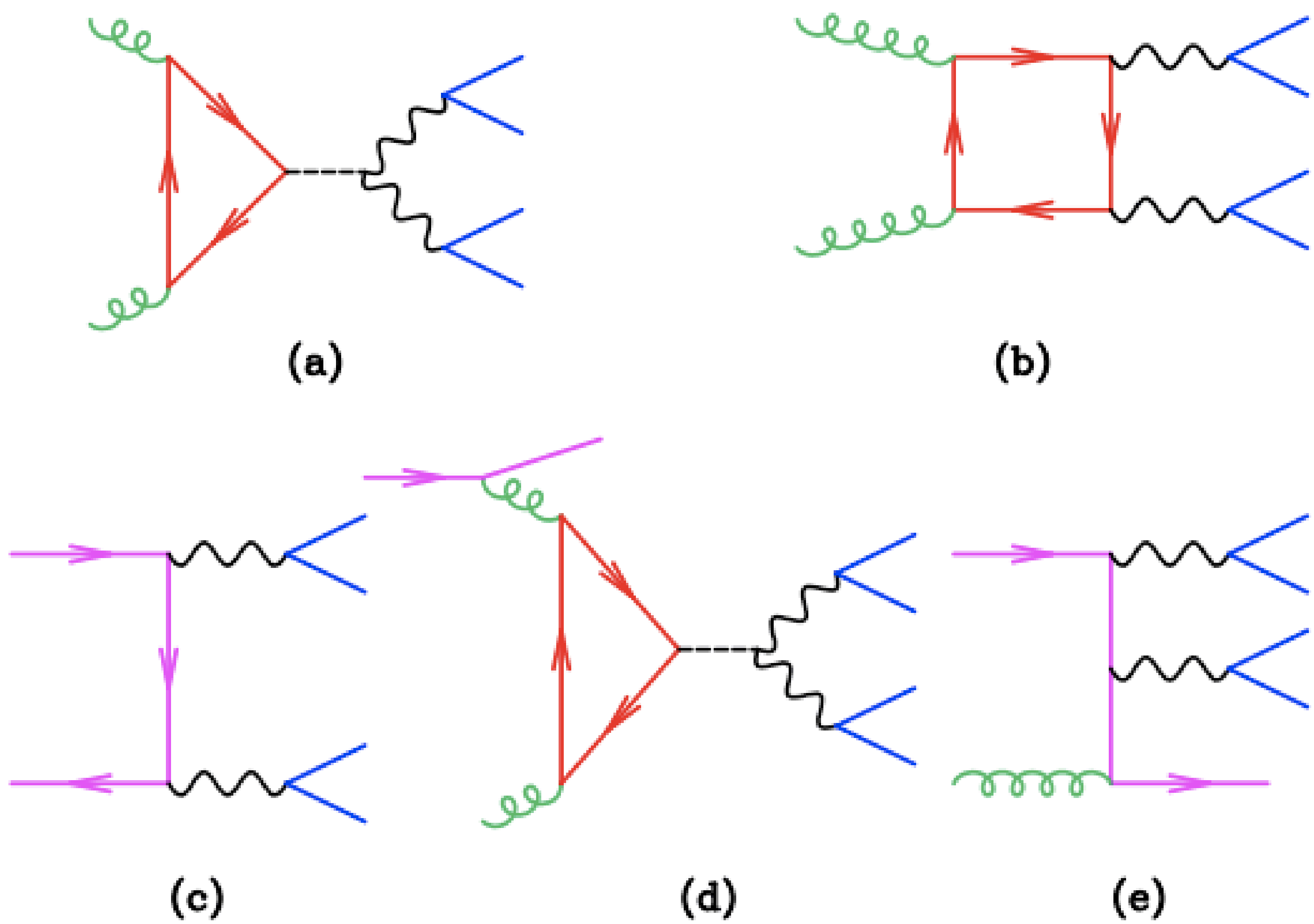




Theoretical ingredients

- Need precision prediction for the 4-lepton final state.

$(a): g(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(b): g(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(c): q(-p_1) + \bar{q}(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(e^4)$
$(d): q(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s^3 e^4)$
$(e): q(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s e^4)$



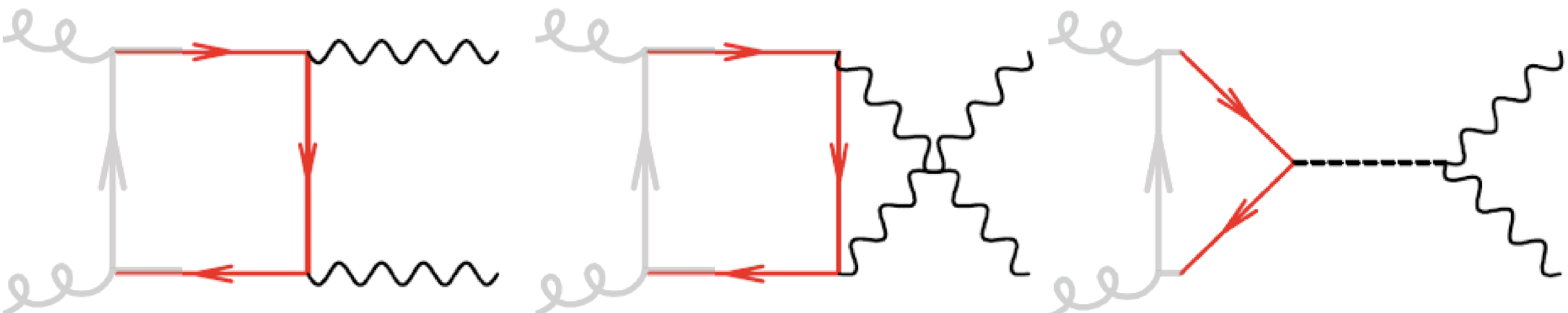
(a)+(b): gluon initiated (signal and background)

(c): dominant background

(d)+(e): “qg interference”, same order as (a)*(b)

Importance of interference

- Usual classification into “signal” and “background” contributions neglects the effect of interference
  - that is particularly important since a Higgs boson is involved.
- Consider high-energy $t\bar{t} \rightarrow ZZ$ scattering (diagrams embedded in loops).
  - straightforward to examine behavior using longitudinal modes of Z’s

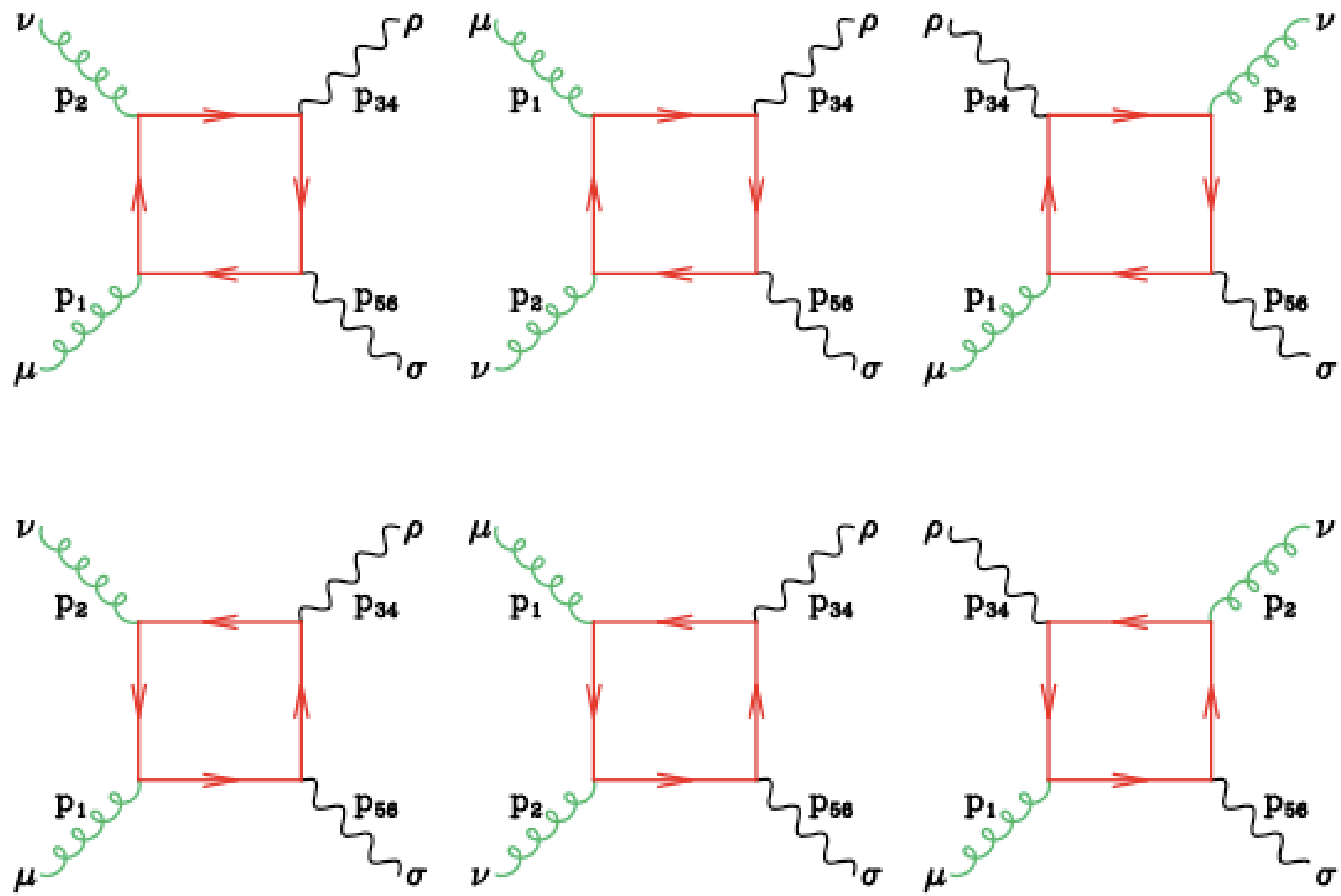


$aE^2 + (b+c)m_t E$ $\qquad$ $-aE^2 + (d-c)m_t E$ $\qquad$ $-(b+d)m_t E$

- Inclusion of Higgs diagram essential to cancel bad high energy behaviour.
- An observation of this mechanism at work would be evidence of the Higgs boson doing its job.

Calculation

- Most contributions are either tree-level or simple 3-point diagrams.
- Most challenging calculation is the gg→ZZ box diagrams.
- Only six basic diagrams; can contract with Z currents later.



- As we've seen, essential to account for quark masses in the loop.
- Classify contributions according to couplings of the Z's to quarks. Mixed vector(V)/axial(A) contribution vanishes, so two independent contributions: either (VV,AA), or in terms of left(L) and right(R) -handed couplings (LL,LR)

$$A_{VV} = 2\left(A_{LL} + A_{LR}\right) \ , \qquad A_{AA} = 2\left(A_{LL} - A_{LR}\right)$$

History

- A long and rich history.
- VV amplitude calculated in 1971 using a dispersive technique.
  Constantini, de Tollis, Pistoni; Nuovo Cim. A2 (1971)
- LR amplitudes in 1989, for strictly on-shell Z's.
  Glover, van der Bij; NPB 321 (1989)
- Extension to off-shell Z-bosons.
  Zecher et al; hep-ph/9404295
- Numerical calculation including leptonic decays.
  Binoth, Kauer, Mertsch; 0807.0024
- Analytic form of amplitudes for massless quarks (only VV relevant).
  Bern, Dixon, Kosower; hep-ph/9708239
- Implementation of all contributions (numerically) in gg2VV code.
  Kauer, Passarino; 1206.4806
- Aim: full analytic calculation for fast and numerically stable evaluation.

LL amplitude

- Bulk of calculation is LL amplitude: use *D*-dimensional unitarity techniques to obtain coefficients of basic integrals.

  Britto, Cachazo, Feng, hep-th/0412103; Forde, 0704.1835

- Expand integral basis to use 6-dimensional scalar boxes:

$$\boxed{\begin{aligned} A_{LL}(1_g^{h_1},2_g^{h_2},3_e^-,4_{\bar{e}}^+,5_\mu^-,6_{\bar{\mu}}^+) &= \sum_{j=2}^{3} d_j^{d=6}(1^{h_1},2^{h_2})\, D_0^{d=6}(j) + \sum_{j=1}^{3} d_j(1^{h_1},2^{h_2})\, D_0(j) \\ &+ \sum_{j=1}^{6} c_j(1^{h_1},2^{h_2})\, C_0(j) + \sum_{j=1}^{6} b_j(1^{h_1},2^{h_2})\, B_0(j) + R(1^{h_1},2^{h_2}) \end{aligned}}$$

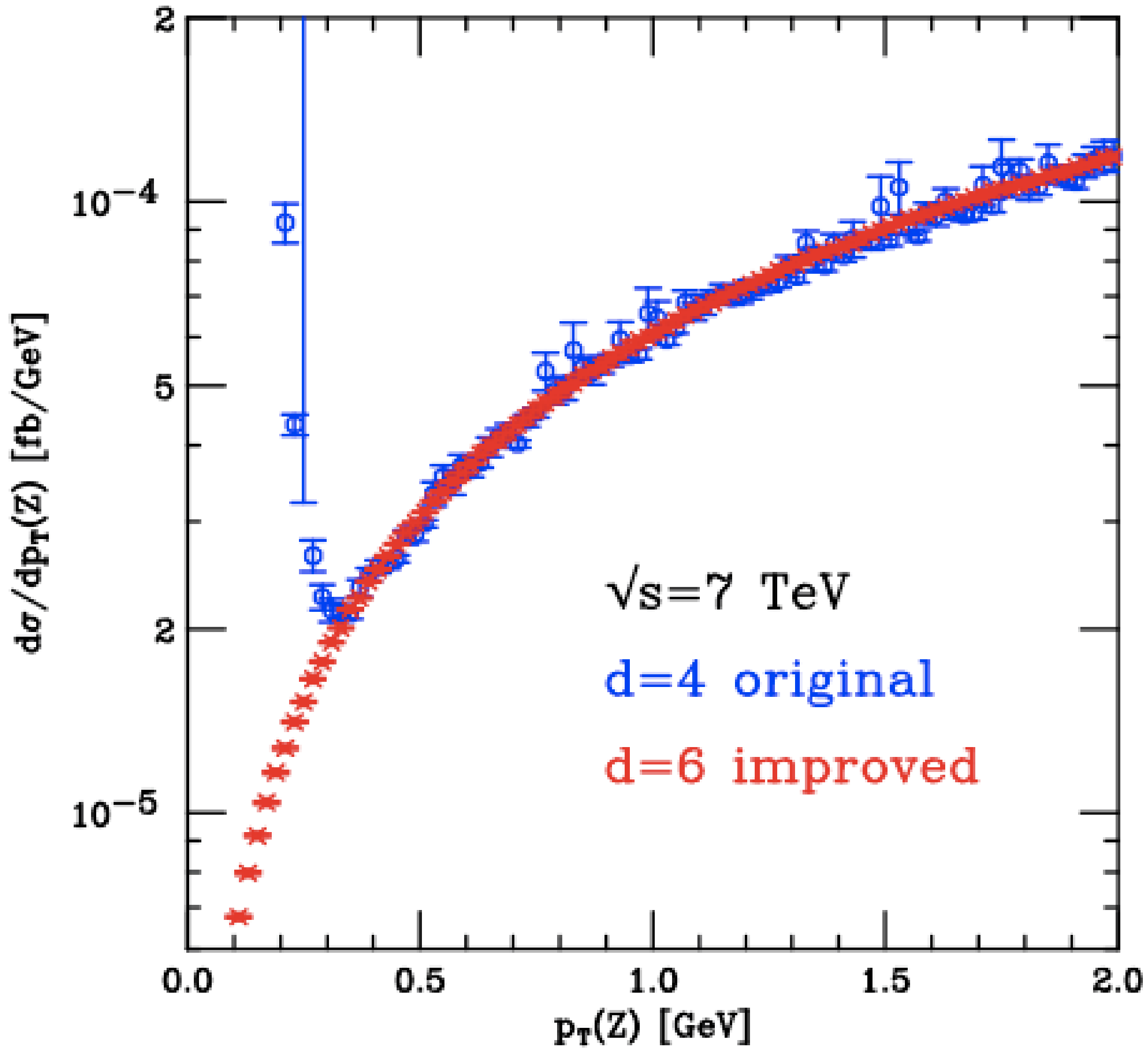
- 6-d box can be expressed in terms of usual 4-d integrals:

$$\begin{aligned} D_0^{d=6}(2) &= \frac{s_{134}}{2Y}\Big[(s_{13}+s_{14})C_0(3)+(s_{25}+s_{26})C_0(6)+s_{12}C_0(1) \\ &+ \left(s_{12}-s_{34}-s_{56}+2\frac{s_{34}s_{56}}{s_{134}}\right)C_0(2) - \left(s_{12}s_{134}+\frac{4m^2Y}{s_{134}}\right)D_0(2)\Big] \end{aligned}$$

- Overall factor of the box Gram determinant: $Y = s_{12}p_T^2 = 4\,p_{34}.p_1\,p_{34}.p_2 - s_{12}s_{34}$
  - in the limit that $Y \to 0$, the scalar integrals combine such that $D_0^{d=6}$ is finite.

Stability

- Taming the singularities by rewriting the amplitudes in the 6-d box basis has tangible benefits in the final code.
- Apparent singularities as $p_T \to 0$ are completely removed for the LR amplitude.
- The LL amplitude contains higher-rank integrals, so some (milder) traces of the problem remain.
- Implementation good down to $p_T(Z)$ of 0.1 GeV.



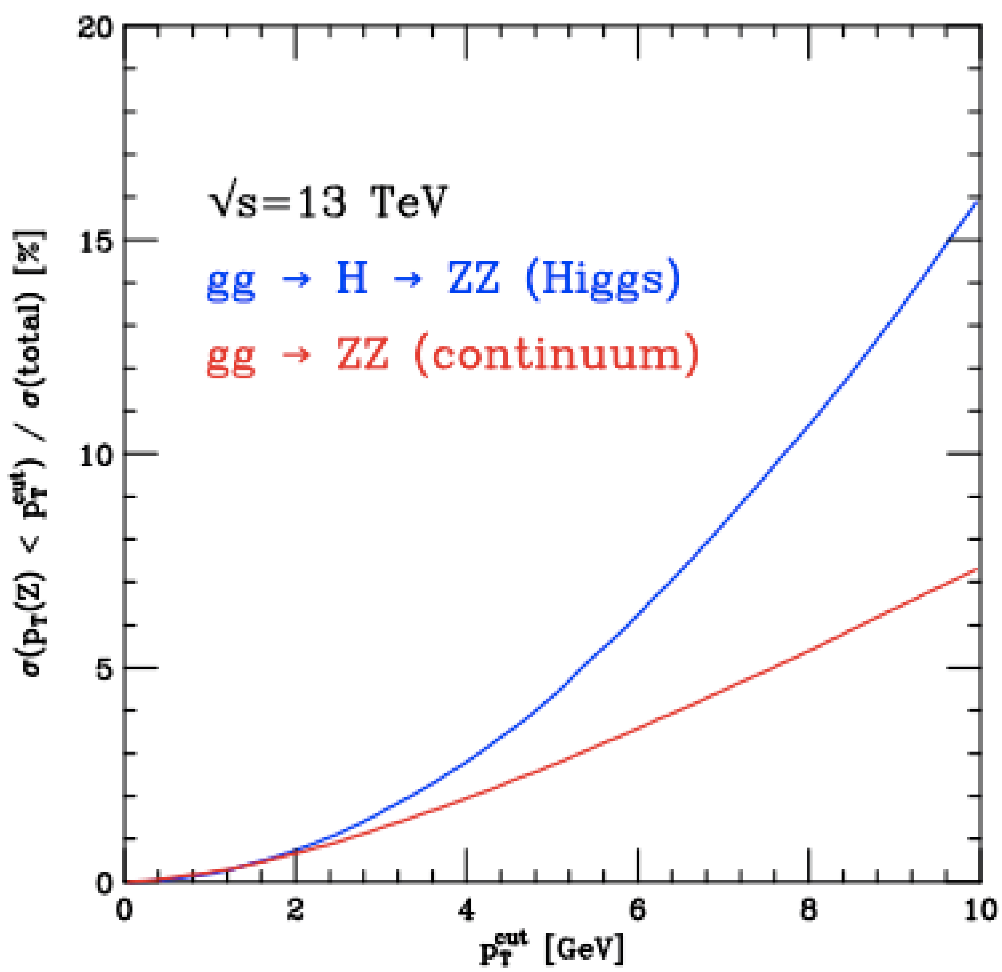
Enforced stability?

- Why not simply place a cut on the transverse momentum of the Z bosons?
- Outside the confines of the calculation, not very well motivated.
  - normal experimental cuts do not especially affect this region, since only lepton decay products are constrained.
- Surprisingly, fairly substantial contribution to the total cross section from the low p_T region.
- Cuts to enforce stability remove unacceptably-large chunk for the level of precision we desire.

cut @ 0.1 GeV → lose < 0.1%

cut @ 1 GeV → lose 0.3%

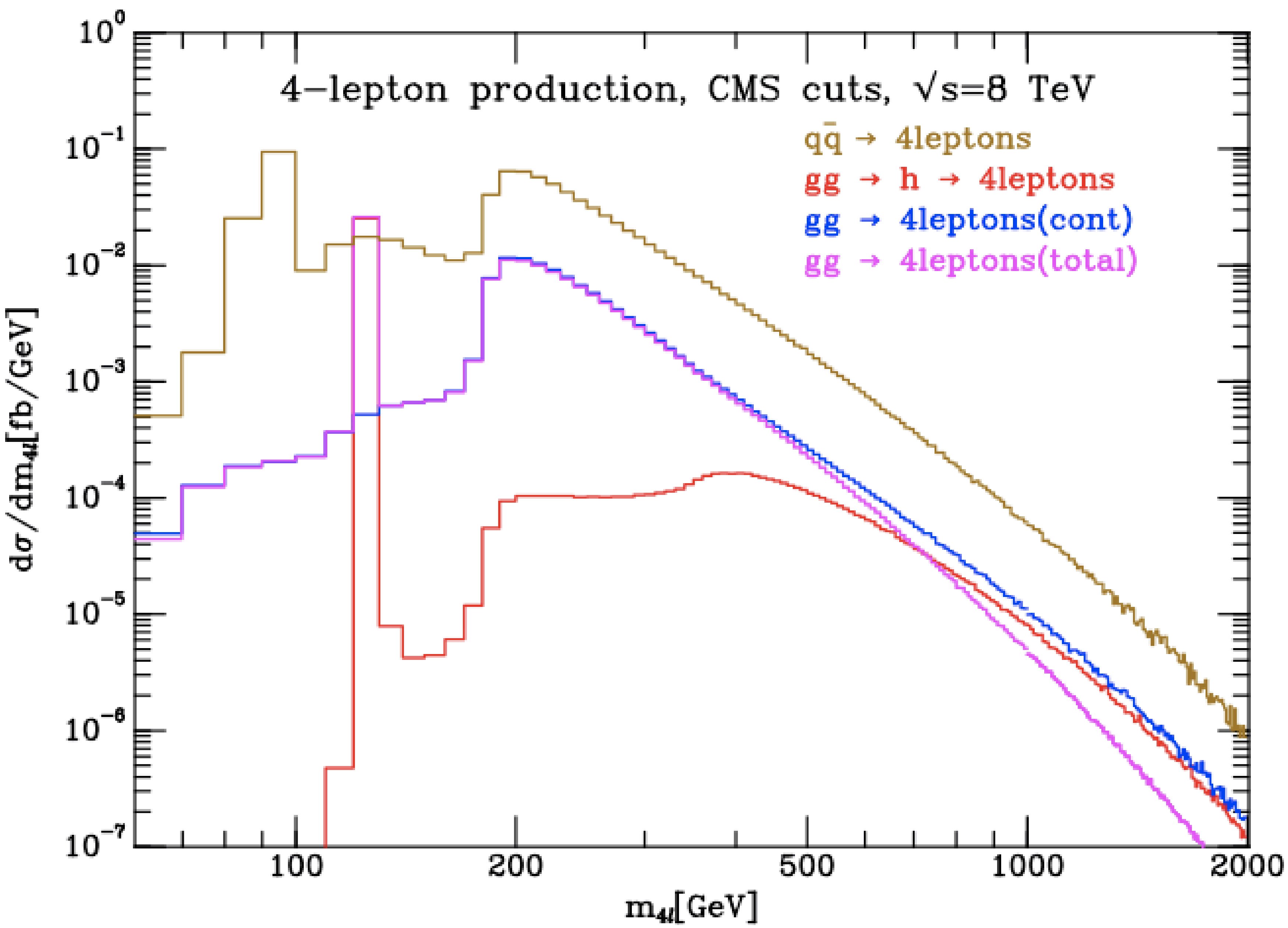
cut @ 7 GeV → lose 5-10%



(essentially the same at other energies)

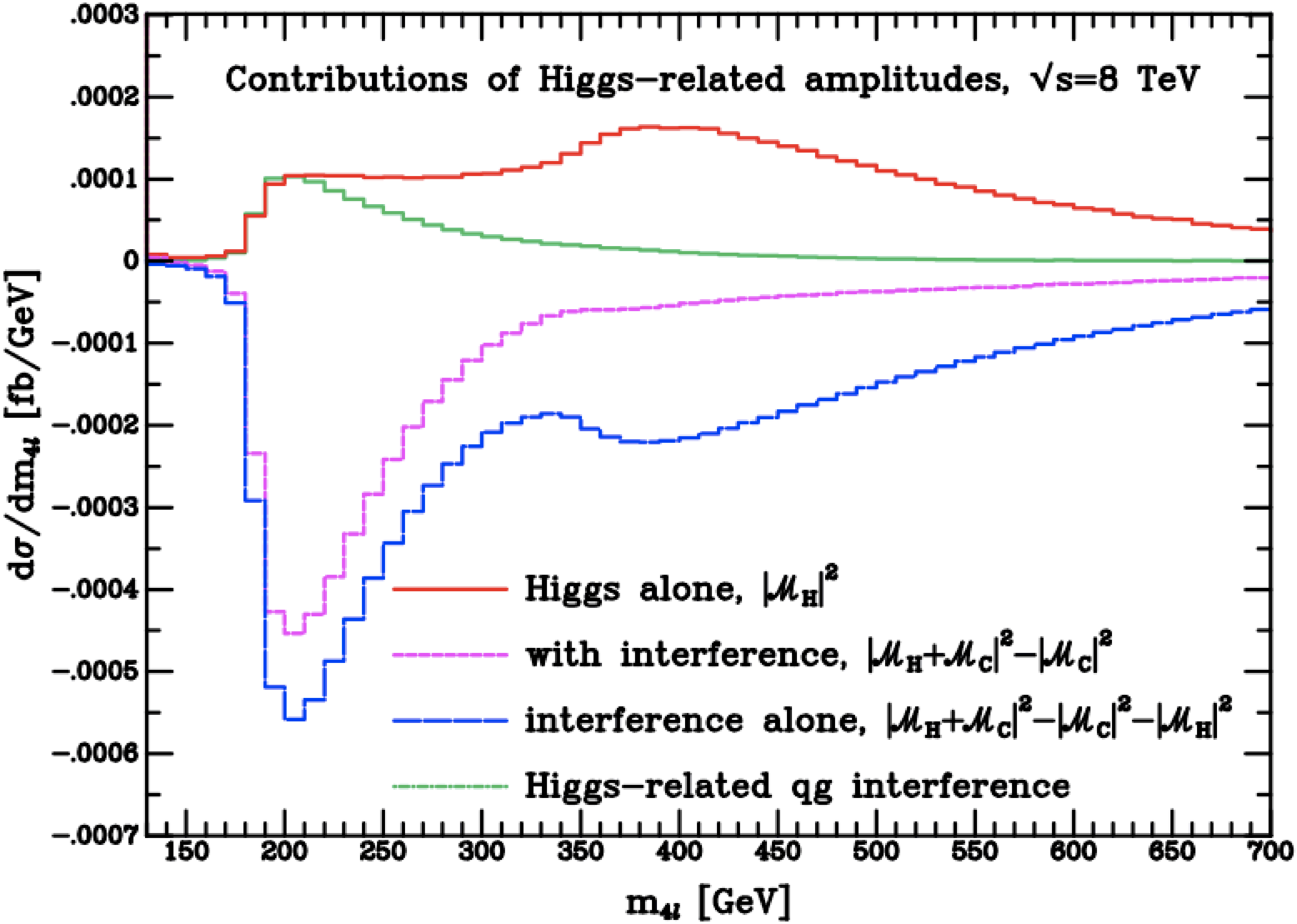
The result

- Cuts appropriate for CMS analysis of full data-set.



- Continuum ($q\bar{q}$) background 1-2 orders of magnitude larger throughout most of range.
- Effect of destructive interference clear for high m_{4l}.
- Difficult to observe effect (in the SM) since strong pdf suppression, so little rate there.

More detail



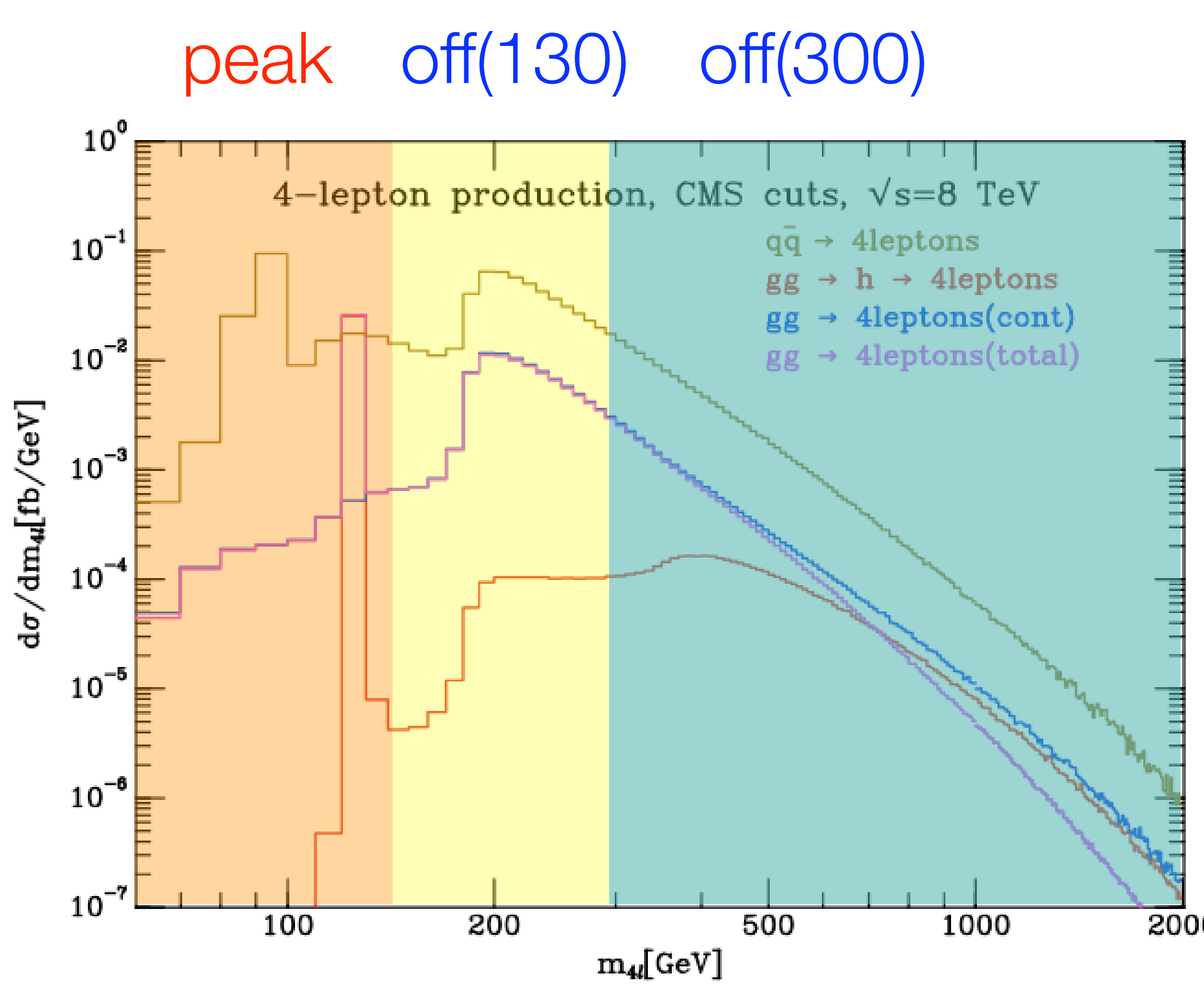
"qg interference" not so important

Cannot describe off-peak region without proper treatment of interference

By the numbers

Energy	PDF	σ^H_{peak}	$m_{4\ell} > 130$ GeV σ^H_{off}	$m_{4\ell} > 130$ GeV σ^I_{off}	$m_{4\ell} > 300$ GeV σ^H_{off}	$m_{4\ell} > 300$ GeV σ^I_{off}
7 TeV	MSTW	0.203	0.025	-0.053	0.017	-0.025
	CTEQ	0.192	0.021	-0.047	0.015	-0.021
8 TeV	MSTW	0.255	0.034	-0.073	0.025	-0.036
	CTEQ	0.243	0.031	-0.065	0.022	-0.031
13 TeV	MSTW	0.554	0.108	-0.215	0.085	-0.122
	CTEQ	0.530	0.100	-0.199	0.077	-0.111

- Define peak region and two (overlapping) off-shell regions.
- Effect of Higgs-induced diagrams on off-shell cross sections slightly larger at 13 TeV.
  - also, grows faster than competing $q\bar{q}$ background.
- Some variation of absolute cross sections with pdfs, but ratio (off-shell)/(peak) rather stable.



Expectation in CMS data

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ± 0.8	13.8 ± 1.0	18.1 ± 1.3	38.5 ± 1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ± 2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ± 2.7
$m_H = 125$ GeV	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0	19.2 ± 1.4
$m_H = 126$ GeV	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1	21.1 ± 1.5
Observed	16	23	32	71

CMS PAS HIG-13-002

Combination of 7 and 8 TeV data

- Repeat analysis of Caola and Melnikov: normalize to CMS peak cross section to obtain prediction for number of off-shell events.

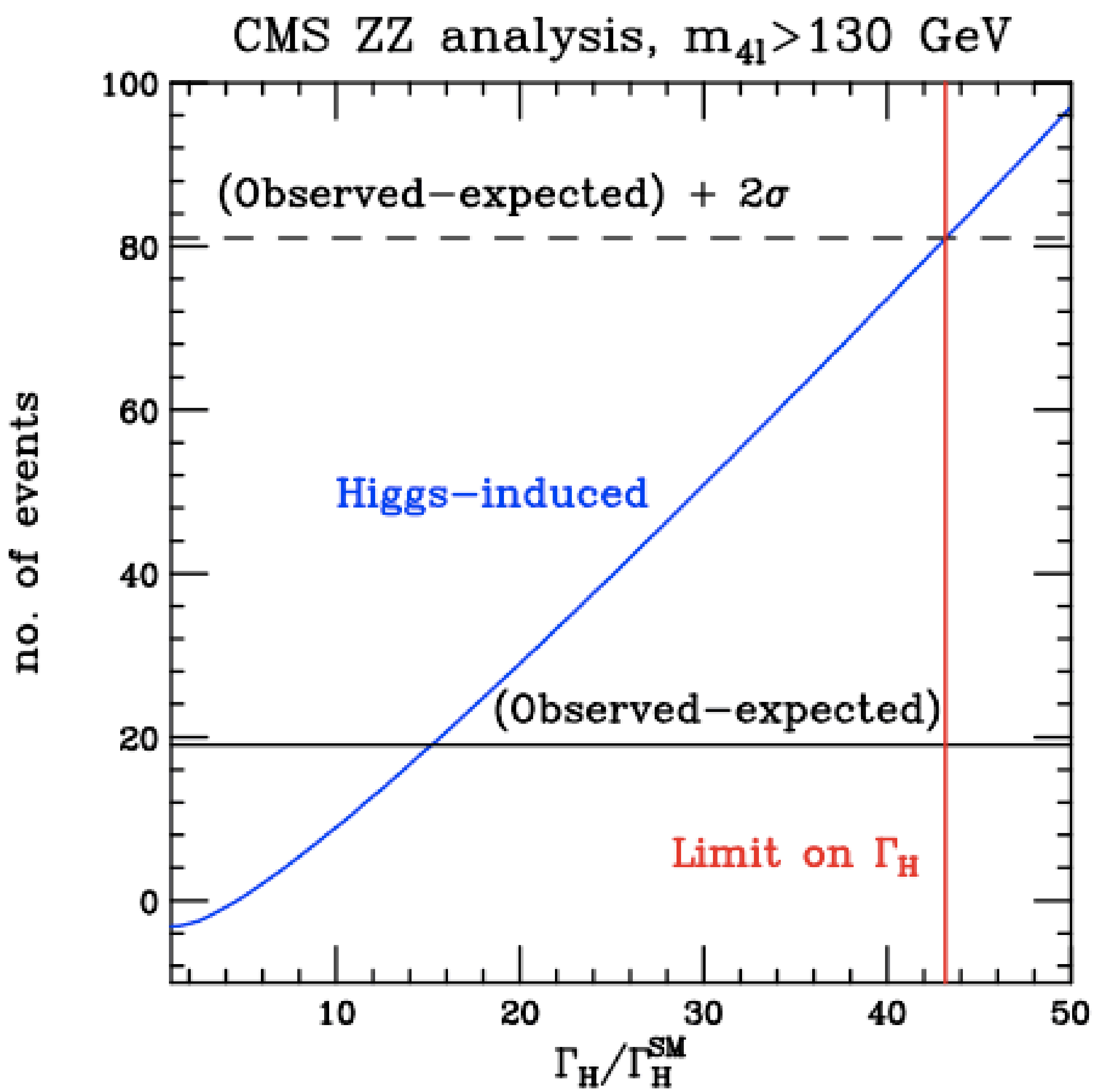
$$N^{4\ell}_{off}(m_{4\ell} > 130\ \text{GeV}) = 2.78\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

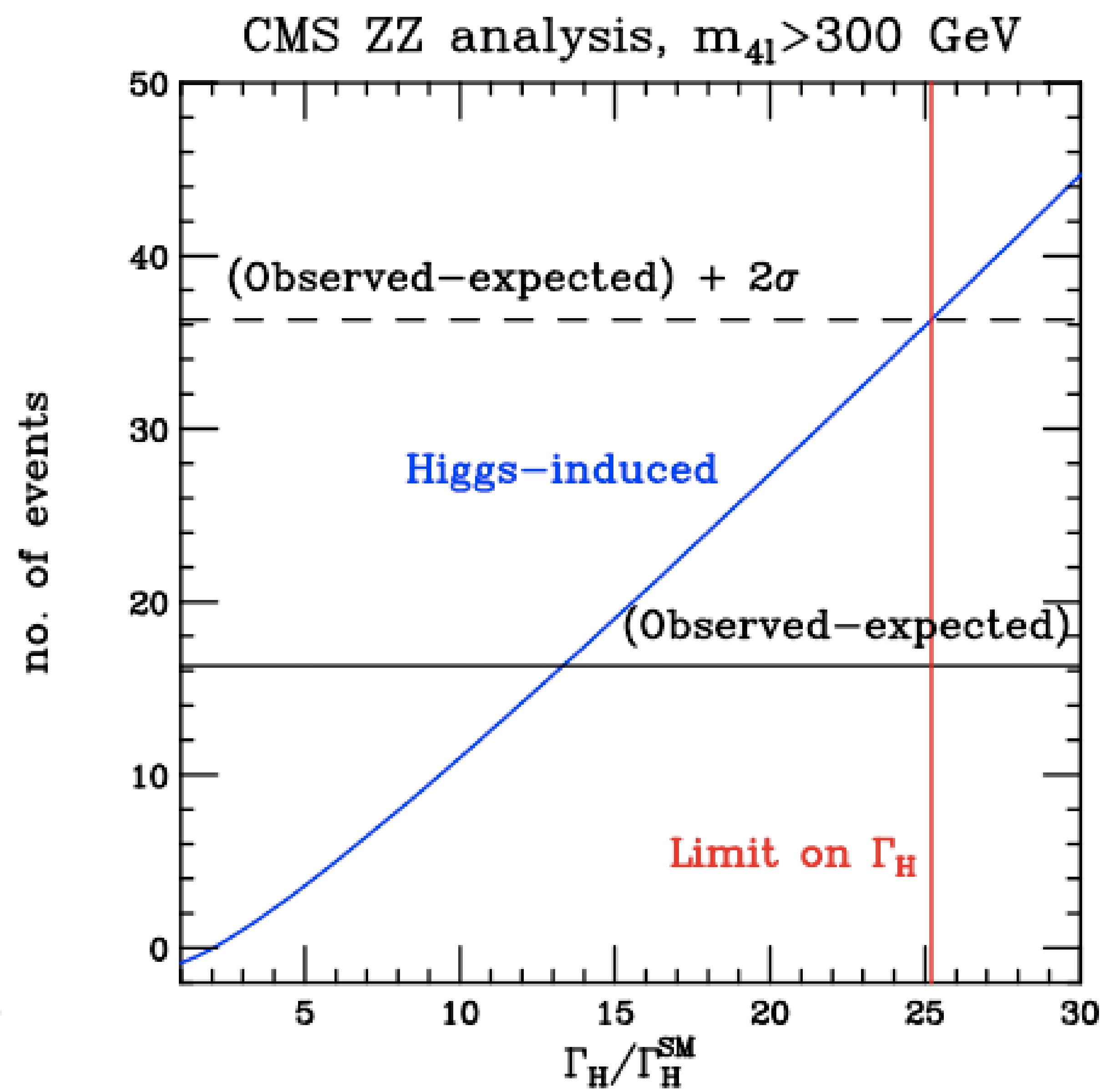
$$N^{4\ell}_{off}(m_{4\ell} > 300\ \text{GeV}) = 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

(expected Higgs events in total CMS data)

- Somewhat different from original Caola-Melnikov analysis:
  - choice of scale, use of gg2VV that inadvertently contained $p_T(Z)$ cut.

Comparison: indicative constraints





expected (no H): 432 ± 31

$$\boxed{\Gamma_H < 43.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

expected (no H): 71 ± (10?)

$$\boxed{\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

Matrix element method improvements

- Cut-and-count is the simplest approach and should improve substantially with more data.
- Meanwhile, use more kinematic information with a matrix element method.

Giele, Williams, JC; 1204.4424

Data event φ

Probability of event under different hypotheses

(integration over equivalent longitudinal boosts to map to 2→4 phase space)

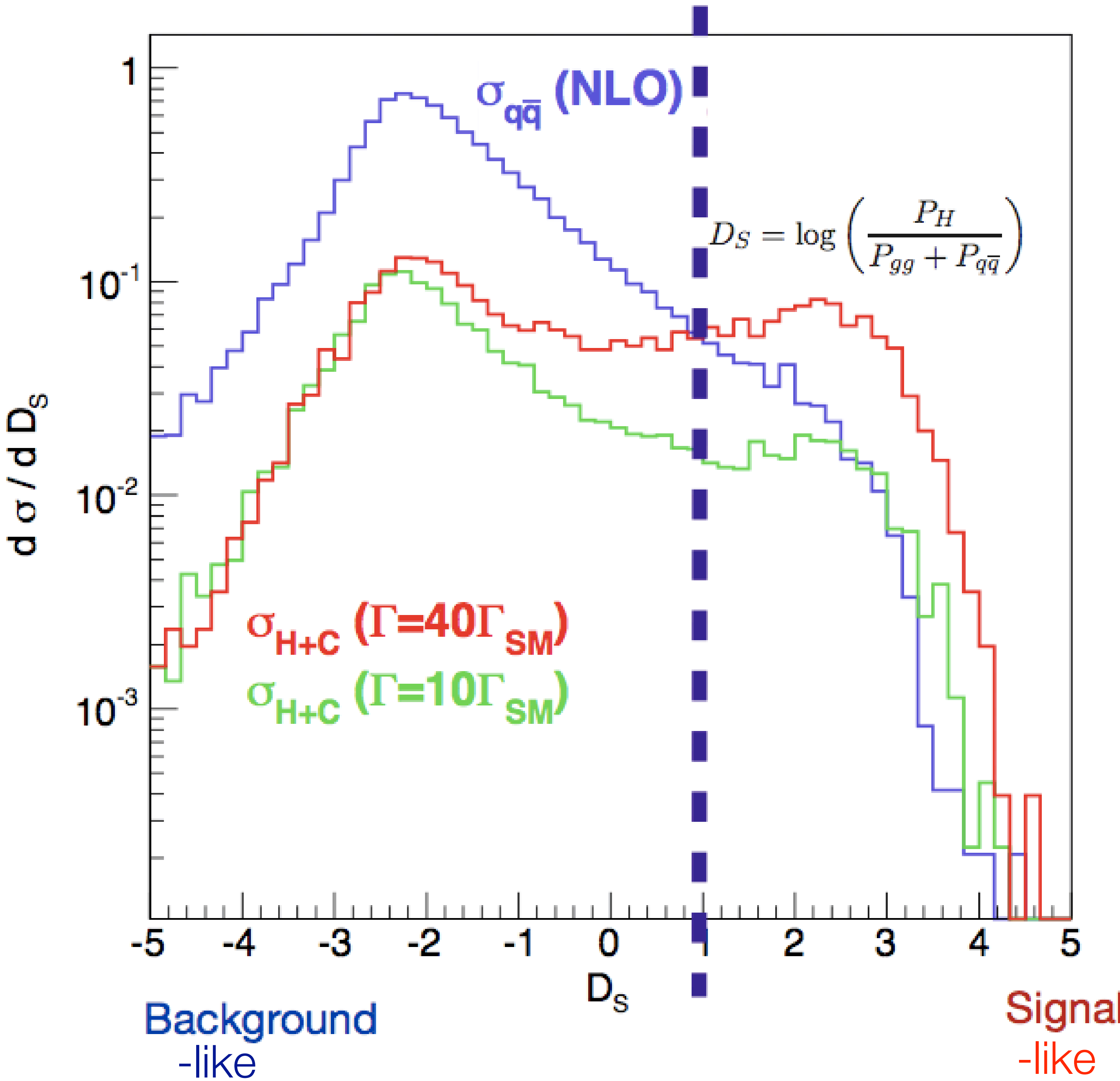
$$P_{LO}(\phi) = \frac{1}{\sigma_{LO}} \sum_{i,j} \int dx_1 dx_2\, \delta(x_1 x_2 s - Q^2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, \phi)$$

$P_{q\bar{q}}$	:	$q\bar{q}$ initiated background.
P_{gg}	:	gg initiated pieces, including Higgs signal, box diagrams and interference.
P_H	:	gg initiated Higgs signal squared.

- Compute discriminant to understand which hypothesis preferred:

$$D_S = \log\left(\frac{P_H}{P_{gg} + P_{q\bar{q}}}\right)$$

MEM simulated analysis



Discriminant effectively isolates gluon-related contributions from $q\bar{q}$ backgrounds.

- a simple cut on D_s would suffice

Number of events passing cut sensitive to the width.

Using an analysis that roughly mimics the CMS results found before, a cut D_S>1 finds:

$$\boxed{\Gamma_H < \left(15.7\ ^{-2.9}_{+3.9}\right)\ \Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

WW

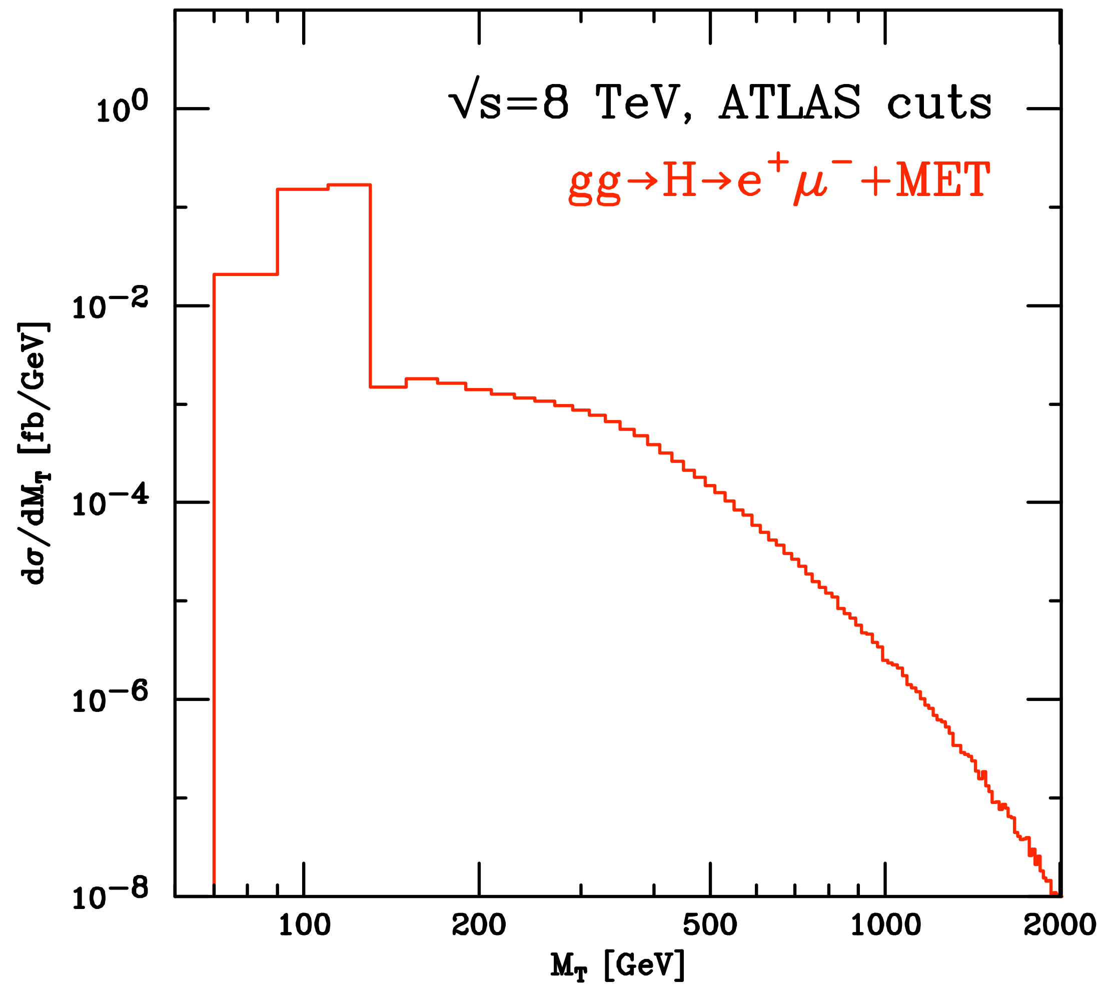
- The ZZ channel is convenient: well-measured leptons allow the Higgs boson lineshape to be mapped out and peak/off-shell regions directly identified.
- However, exact mapping of lineshape is not crucial, just need well-separated regions corresponding to on- and off-resonance.
- Try to play the same game in WW channel:

$$gg \to W^+W^- \to e^+\mu^-\nu_e\bar{\nu}_\mu$$

- As proxy for invariant mass, use transverse mass of expected WW system:

$$M_T^2 = (E_T^{miss} + E_T^{\ell\ell})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2$$

- Some features washed out, but clear separation between peak and tail remains.



WW vs ZZ

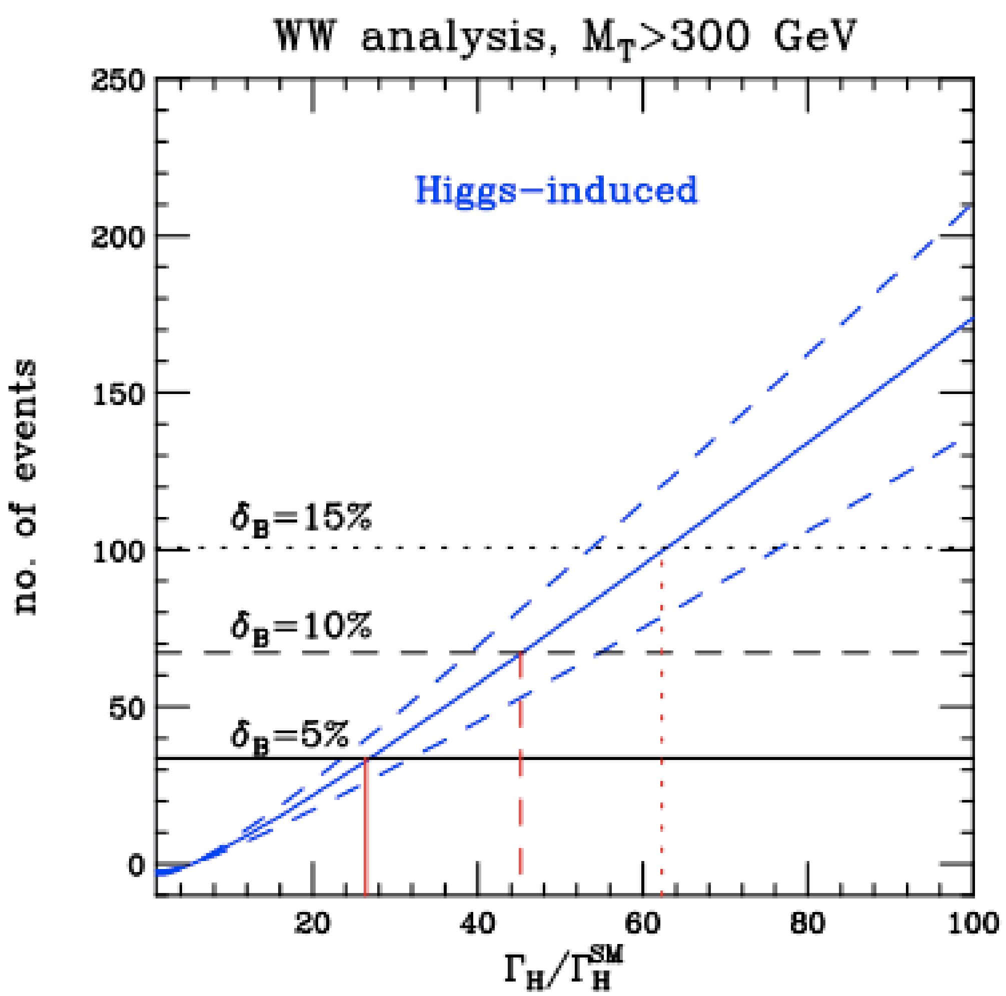
- Advantages:
  - threshold for two real W's much closer than for two real Z's
  - branching ratio into leptons also larger
  - combined, two orders of magnitude more events:

$$\mathrm{Br}(H \to WW) \times \mathrm{Br}(W \to \ell\nu)^2 = 2.7 \times 10^{-3}$$
$$\mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to \ell^+\ell^-)^2 = 3.2 \times 10^{-5}$$

- Disadvantages:
  - much less clean so many more backgrounds
  - particularly, top-related that require a jet-veto to control
  - as a result, even observation of the Higgs boson in this channel alone not yet confirmed.

Estimate of sensitivity

- Cuts to isolate Higgs peak signal remove tail, so some cuts must be lifted.
- Requires more of a leap of faith than ZZ estimates, since ATLAS uncertainties only presented in the resonance region.
- Extrapolation, estimation of backgrounds, systematic uncertainties, ...



- <B>=336 events
- Try to be conservative by using systematic uncertainty on theory and your choice of experimental systematic uncertainties.

$$\boxed{\Gamma_H < 45^{+9}_{-7}\,\Gamma_H^{SM}}$$

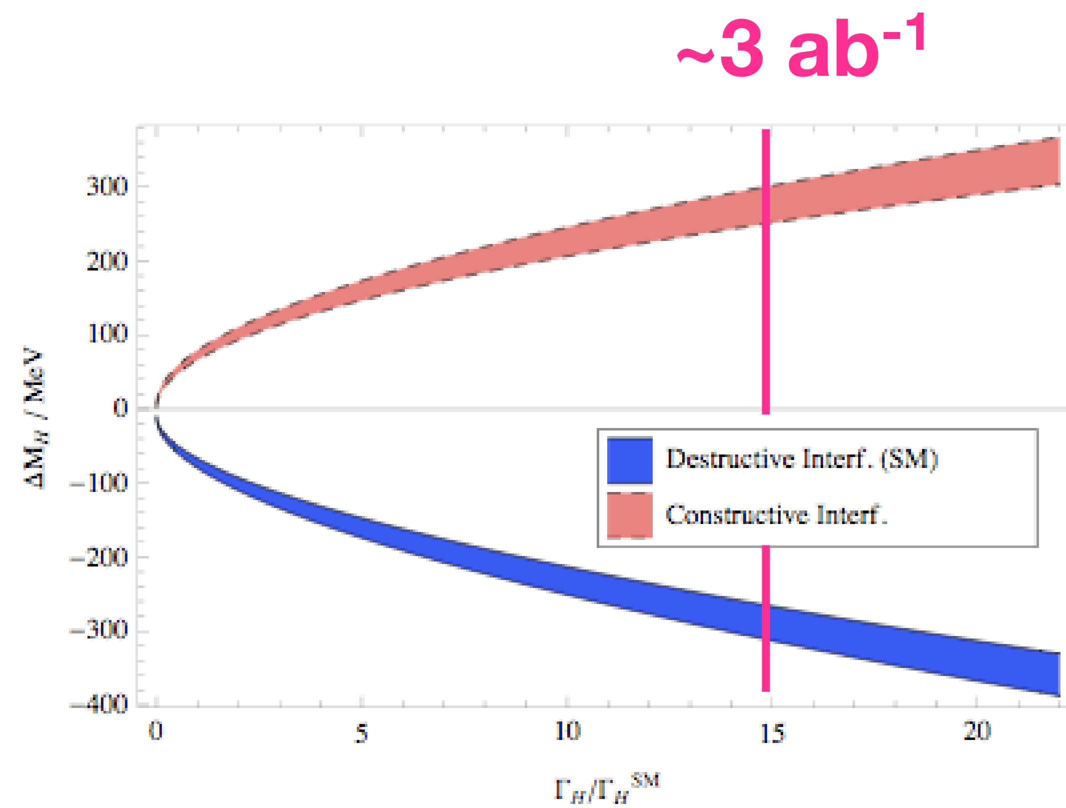
- Different flavour, 20 fb^{-1}, δ_B=10%.

Other approaches

- Direct: interferometry in diphoton decay; interference induces change in diphoton mass distribution that depends on the width.

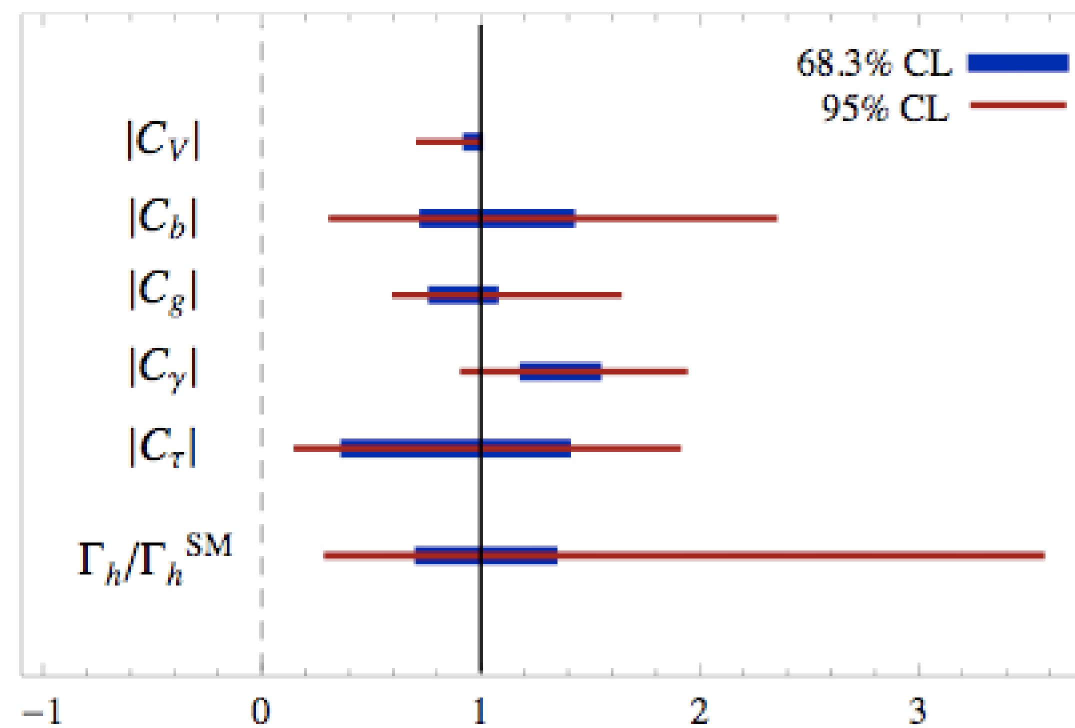
  Dixon, Li; 1305.3854

- Require precise measurement of mass shift between ZZ and diphoton channels.



- Indirect: global coupling fits; assume either that the coupling to W,Z takes the SM value, or is bounded by reasonable theoretical assumptions.

  Dobrescu, Lykken; 1210.3342



Projections pre-Moriond 2014

LHC run I

Method	Measured quantity	Γ_H [MeV]	$\Gamma_H/\Gamma_H^{\mathrm{SM}}$
CMS-PAS-HIG-13-016	Width $\times$ resolution	< 6900	< 1600
1305.3854 (Dixon-Li)	Mass shift in $\gamma\gamma$, $\Delta m_H \sim 1$ GeV	< 800	< 200
1312.1628 (CEW)	Ratio WW, $m_T > 130$, 300 GeV	$< 500, 180$	$< 125, 45$
1311.3589 (CEW)	Ratio ZZ, $m_{4\ell} > 130$, 300 GeV, MEM	$< 170, 100, 60$	$< 43, 25, 15$

LHC 3ab^{-1}

Method	Measured quantity	Γ_H [MeV]	$\Gamma_H/\Gamma_H^{\mathrm{SM}}$
Snowmass estimate 3 ab^{-1}	Width $\times$ resolution	< 200	< 50
1305.3854 (Dixon-Li) 3 ab^{-1}	Mass shift in $\gamma\gamma$, $\Delta m_H \sim 100$ MeV	< 60	< 15
1307.4935 (CM) 3 ab^{-1}	Ratio ZZ, $m_{4\ell} > 130$, 300 GeV	$< 40, 20$	$< 10, 5$

Commentary

- The effect of the box diagram interference is computed at LO.

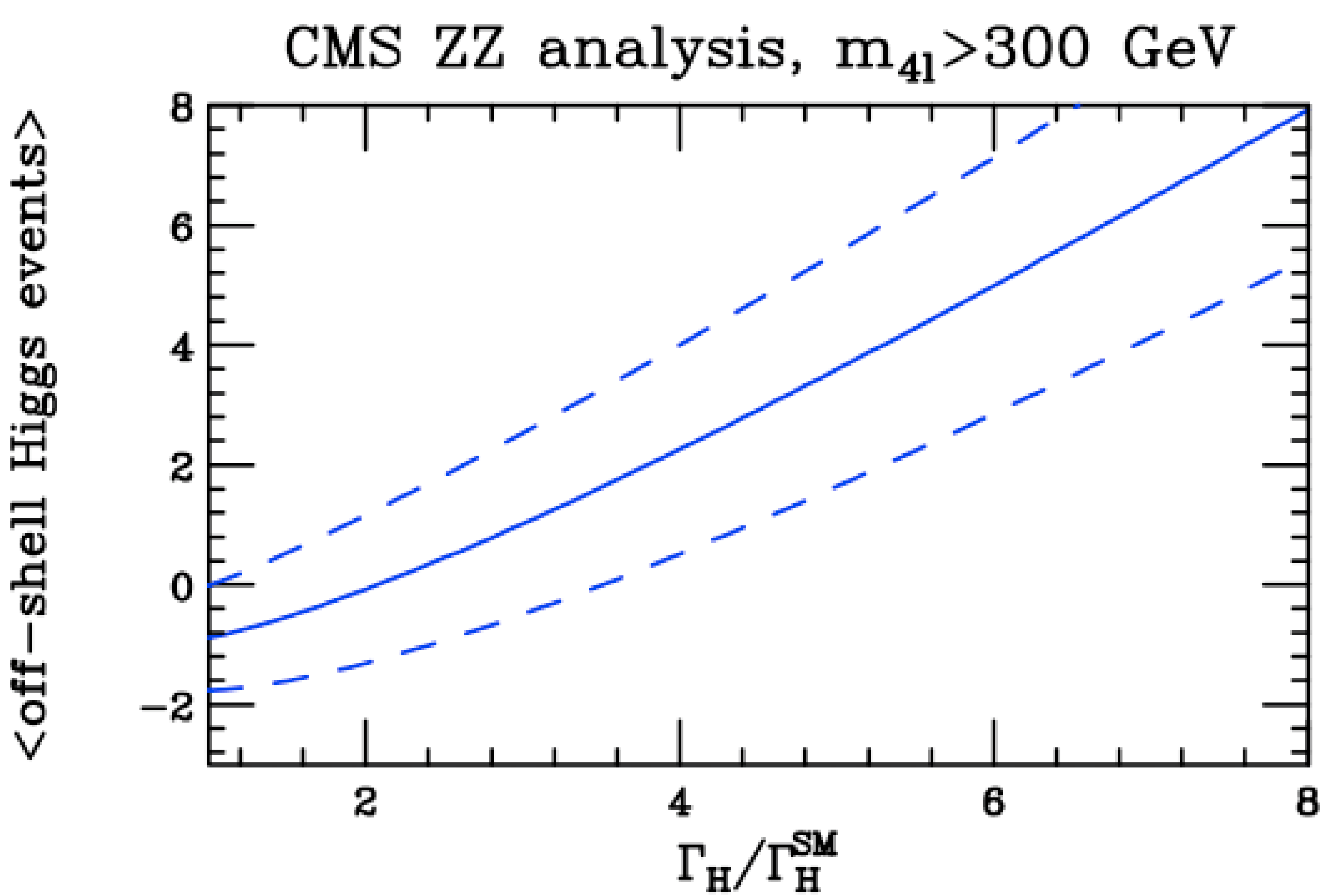
$$N_{off}^{4\ell}(m_{4\ell} > 130 \text{ GeV}) = 2.78 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$
$$N_{off}^{4\ell}(m_{4\ell} > 300 \text{ GeV}) = 2.02 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

- For widths much bigger than the SM effect of the interference is small, but CMS result already close to SM value.
- By normalizing to the observed cross section, implicitly assume that the effect of higher order corrections is the same in interference as in the square.
- This assumption appears to be approximately confirmed by a soft-collinear approximation of the NLO and NNLO result for *gg→H→WW for a heavy Higgs boson*.

  Bonvini et al; 1304.3053
- This conclusion adopted by CMS; additional 10% systematic uncertainty assigned to rates.

Impact of uncertainty on interference

- Hard to model higher-order corrections except by impact on rates.
  - for the real answer, must of course do the calculation.
  - NLO interference means 2-loop virtual and 1-loop real radiation.
- In the meantime, can estimate impact on cut-and-count result by changing interference term by ± 30% (rather modest for a LO prediction).



Example:

Default: 2 extra events → interpret bound at 4 x SM

± 30%: 2 extra events → limit interval (2.5 - 5.5) x SM

Summary

- Impressive new direct limits on width of the Higgs boson at a level that was completely unexpected 1 year ago.

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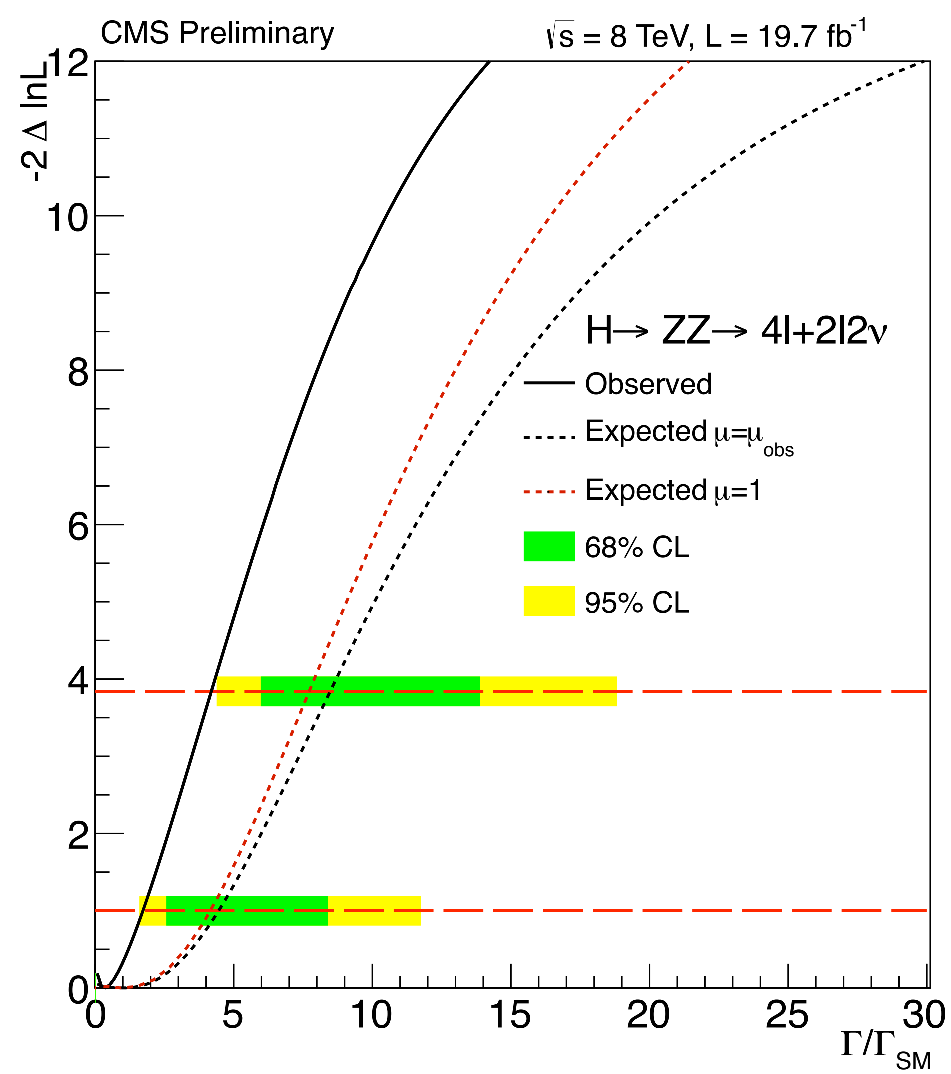

$\mathbf{\Gamma_H < 4.2 \times \Gamma_H^{SM}}$ at 95% confidence

- Prospects for immediate improvement in these channels (ZZ→4ℓ, 2ℓ2v) not clear:
  - observed limit < expected limit
  - limit already becoming sensitive to shortcomings of theory prediction
- Other channels?
  - ZZ→2ℓ2q not yet studied (either exp. or theory); has additional background and interference contributions (Z+2j).
  - WW no exp. result yet.